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Millimeter-Wave Communication for Autonomous Driving: Principles, Applications, and Challenges

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Abstract:

With the development of autonomous driving technology and the construction of smart cities, vehicle-to-everything (V2X) communication has emerged as a key enabler for ensuring reliable autonomous vehicle operations. Due to advantages such as high bandwidth and low latency, millimeter-wave (mmWave) communication has become an important means of communication in driverless cars. At present, many scholars have carried out a lot of experiments and research around the application of mmWave communication in unmanned driving. This paper analyses the basic principles of mmWave communication and comprehensively discusses these studies and models. These studies provide guidance for the application of mmWave communication in autonomous driving technology. It also summarizes the challenges faced by mmWave communications in unmanned vehicles, such as bad weather and high mobility challenges. Additionally, the paper explores how emerging 6G communication paradigms can be leveraged to address the limitations of mmWave systems, particularly in the context of evolving vehicular communication infrastructures.

Keywords: Millimeter-wave communication; Autonomous driving; Antennas; Multi-sensor fusion and cooperative sensing.

1. Introduction

At present, the enhancement of vehicle communication and perception capabilities, combined with the rapid development of key technologies, such as sensing, communication and control, is driving the Vehicular Network to become the core part of the Intelligent Transportation System (ITS). The Vehicular Network enables vehicles, Roadside Unit (RSU), pedestrians, traffic management centers and related entities to gain comprehensive awareness of the surrounding environment through Vehicle-to-Vehicle Communication(V2V), Vehicle-to-Vehicle Communication(V2I), Vehicle-to-Pedestrian Communication(V2P) and other communication methods. At the same time, it facilitates the rapid exchange and sharing of information among these entities, meeting their demands for low latency, high throughput, and reliable communication. In the end, the network leads to a significant improvement in both traffic efficiency and driving safety levels, and provides foundational support for connectivity and communication within ITS.

As a core technology in autonomous driving, millimeter-wave (mmWave) communication requires in-depth research and analysis to define potential application directions and pinpoint upcoming technical obstacles. Such research can lead to critical breakthroughs, foster the systematic integration of academic knowledge, and offer valuable guidance for advancing autonomous driving technologies. Additionally, this will accelerate the modernization of transportation and infrastructure.

This paper explores the topic from the perspective of fundamental electromagnetic theory, focusing on mmWave communication, which is a key enabling technology in autonomous driving. The analysis encompasses the fundamental principles of mmWave communication, high-performance antenna characters for vehicular applications, channel propagation characteristics, and the impact of complex weather conditions on signal transmission. Additionally, this paper investigates the corresponding technical challenges in autonomous driving. This study aims to construct a comprehensive system for mmWave communication tailored to autonomous driving, offering theoretical foundations and actionable guidance for optimizing routing strategies and exploring application scenarios.

2. Fundamental Theory of mmWave Communication

2.1 Electromagnetic Properties

The mmWave spectrum ranges from 30 to 300 GHz, classified as the Extremely High Frequency (EHF) band. These frequencies correspond to wavelengths between 1 and 10 millimeters, placing them within the microwave portion of the electromagnetic spectrum.Millimeter waves offer several significant advantages for wireless communication. The high directionality of mmWave signals allows for efficient transmission with lower power consumption and reduced interference. Moreover, the high directionality of mmWave signals enables autonomous vehicles to establish precise point-to-point communication links with roadside infrastructure. In addition, the mmWave spectrum provides a large amount of available bandwidth, supporting ultra-high data transmission rates necessary for real-time vehicular communication. Finally, the short wavelengths of mmWave signals allow for the implementation of compact and high-gain antenna arrays, which facilitate efficient beamforming techniques [1].

2.2 System Components

Mmwave communication systems typically comprise four core modules: the transmitter, receiver, antenna array, and wireless transmission channel.

The transmitter is responsible for converting baseband signals into modulated radio frequency (RF) signals. This procedure usually entails signal processing activities including digital-to-analog conversion, up-conversion to the mmWave band, and power amplification, prior to the signal being transmitted through the antenna.

The receiver performs the inverse operation of the transmitter. It captures the incoming RF signal through the antenna, down-converts it to an intermediate or baseband frequency, and processes it for demodulation and decoding.

The antenna system serves as the interface between the electronic circuitry and the propagation environment. At the transmitter, the antenna radiates the RF signal into free space, while at the receiver, it captures the incoming electromagnetic waves. In mmWave systems, phased-array antennas are often employed to achieve directional beamforming and spatial multiplexing.

The wireless transmission channel refers to the physical medium through which electromagnetic waves propagate between the transmitter and receiver. In mmWave systems, the channel is strongly influenced by environmental factors such as obstacles, reflections, scattering, and atmospheric absorption. Accurate modeling of the mmWave channel is crucial due to its susceptibility to blockage and high path loss.

2.3 Antenna Technologies

In mmWave systems for autonomous driving, antennas serve as key components for both signal radiation and reception. Their design must consider factors such as propagation characteristics, system integration, and bandwidth performance. Therefore, high gain and narrow beamwidth are essential antenna characteristics in mmWave communication systems, as they enhance signal robustness and reduce interference. Therefore, high gain and narrow beam are the basic requirements for antennas in communication systems to improve important properties such as interference immunity.

The theoretical foundation of antennas comes from classical electromagnetic theory, which is described by Maxwell's equations. Under these conditions, Maxwell's equations in differential form become:

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$$\begin{cases} \nabla \times \mathrm{E} = -\mathrm{j}\omega \mathrm{B} \\ \nabla \times \mathrm{H} = -\mathrm{j}\omega \mathrm{D} + \mathrm{J} \\ \nabla \cdot \mathrm{D} = \rho \\ \nabla \cdot \mathrm{B} = 0 \end{cases} \quad (1)$$

The first step in antenna design is to consider key performance parameters. These parameters include gain, directivity, beamwidth, and bandwidth, all of which directly affect the antenna's communication performance. These metrics also influence the antenna's radiation efficiency and other key electrical characteristics.

In the past, enterprises primarily employed aperture antennas, including horn antennas, reflector antennas, and lens antennas. These types of antennas exhibit strong directivity and were therefore widely used in satellite communications for an extended period. However, conventional antenna structures encounter integration difficulties as the operating frequency rises. As a result, they are not suitable for monolithic integration. To meet mmWave communication requirements, antenna designs must simultaneously achieve compactness and high directivity.

Therefore, research efforts in recent years have increasingly focused on the design and optimization of microstrip antennas. The planar structure of microstrip antennas makes them especially suitable for mmWave systems, as it facilitates seamless integration with other circuit components. Additionally, microstrip antenna dimensions can be adjusted to meet specific requirements in terms of resonant frequency, impedance matching, and radiation pattern [2].

2.4 Large-Scale Propagation Effects

Large-scale propagation effects refer to the general trends of signal attenuation over long distances, typically caused by path loss and environmental shadowing. The log-distance path loss model can be used to better fit path loss measurements by theorizing the log-distance slope in the far field. The log-distance path loss model written as:

$$P_r(d) = P_t K_{fs} \left(\frac{d_0}{d}\right)^{\alpha} \quad \text{for } d \geqslant d_0 \quad (2)$$

Where d is the propagation distance and $d0 \gg \lambda$ is a close-in free space path loss reference distance in the far field. K_fs is the dimensionless constant and α is path loss expo-nent (PLE). Additionally, an aspect of comparable significance is the influence of environmental shadowing. Shadow fading is typically modeled as a log-normal random variable added to the deterministic path loss model. Large obstacles cause electromagnetic shadowing, where the field intensity drops significantly behind barriers (e.g., buildings, vehicles). The phenomenon arises from multiple electromagnetic mechanisms, such as reflection, scattering, and diffraction, triggered when waves encounter physical objects. The electrical conductivity and material composition of the surrounding surroundings have a significant impact on the extent of shadow fading. Diffraction is the propagation of radio signals around an object. At mmWave frequencies, even small movements of a few centimeters can result in considerable signal loss. These mechanisms play a critical role in determining link stability in high-frequency wireless systems, particularly in dynamic environments.

Meanwhile, reflections can either enhance or attenuate the primary signal, leading to constructive or destructive interference that may improve or degrade the received signal quality. The extent of scattering is determined by the electromagnetic properties of obstacles. To overcome high path loss and limited diffraction, beamforming and precise antenna alignment are essential to ensure effective energy transfer. These factors underscore the importance of directional transmission in mmWave communication systems. Consequently, directional transmission becomes a critical requirement.

2.5 The small-scale channel model

In mmWave communication, small-scale channel effects refer to rapid variations of the received signal caused by multipath propagation, often within a few wavelengths of movement. At high frequencies, electromagnetic (EM) waves experience constructive and destructive interference due to the superposition of multiple delayed signal components.

Due to the short wavelength of mmWave signals, small movements of the transmitter, receiver, or surrounding objects can lead to significant changes in signal amplitude and phase. Fading phenomena such as Rayleigh and Rician fading occur when EM waves arrive from multiple angles with random phase shifts.

Additionally, frequency selectivity becomes prominent when the delay spread is comparable to the symbol period, requiring advanced equalization techniques. To characterize the complex electromagnetic behavior in such environments, researchers typically model the multipath propagation using power delay profiles (PDP). PDPs describe the distribution of received signal power over excess delays and can be used to derive parameters such as coherence bandwidth to assess the frequency selectivity of the channel.

For multipath propagation channel characterization, the pseudo-complex baseband equivalent channel $he(t)$ written as:

$$h_e(t) = \sum_{l=1}^{L} h_e[l] \delta(t - \tau[l]) \quad (3)$$

The complex coefficients of each multipath component

$he(t)$ incorporate the large-scale propagation path loss effects from the previous section. The impulse response delineates the arrival times and amplitudes of multipath components arising from environmental reflections, scattering, and diffraction.

The delay spread quantifies the temporal dispersion of multipath components in a wireless channel and is a key metric for characterizing frequency selectivity.

3. Applications in Autonomous Driving

3.1 Outdoor Region-Specific Channel Model

Mmwave signal propagation is extremely sensitive to environmental variations, especially in outdoor vehicular scenarios, where line-of-sight (LOS) conditions, reflective surfaces, and physical obstacles can change drastically from region to region.

To accurately characterize these differences, outdoor channel models are developed with region-specific parameters that distinguish environments such as urban canyons, suburban streets, and highways. These models take into account a variety of location-dependent factors, such as frequency-dependent path loss, shadow fading, multipath richness, and occlusion probability, to provide a realistic basis for the design and simulation of autonomous driving systems.

In support of developing these models, researchers have conducted a number of empirical measurement campaigns in real outside settings. Ref.[3] examined the lifetime, power, and directional variations of multipath components for mmWave communications in a roadway canyon using a SIMO configuration. However, the study was limited to a single street canyon under line-of-sight (LoS) conditions, restricting its generalizability. In 2017, R. Wang and his team conducted extensive measurement campaigns at 28 GHz mmWave in an urban microcellular outdoor environment. To extend previous studies that utilized dense spatial sampling, the team investigated the spatial stationarity of shadowing, Power Delay Profiles (PDPs), and angular spectra [4].

In Downtown Brooklyn, USA, Shakya et al. conducted a comprehensive urban microcellular propagation measurement campaign at 6.75 GHz and 16.95 GHz. These studies have contributed to the development of outdoor-specific channel models tailored for mmWave-based autonomous driving systems. By comparing their region-specific channel model with the 3GPP standard, the study observed a decreasing trend in both root-mean-square (RMS) delay spread and angular spread as the carrier frequency increased [5].

These findings highlight the necessity of region-specific outdoor channel models for accurate evaluation of V2X communication performance in real-world scenarios. Outdoor channel models provide critical EM-layer data for building V2X simulation platforms, supporting beam alignment, routing algorithms, and connectivity reliability assessments in self-driving car networks.

3.2 Multi Sensor Fusion & Cooperative Perception

In autonomous driving systems, mmWave communication provides key support for multi-sensor fusion and cooperative perception. These technologies allow vehicles and infrastructure elements to exchange data, facilitating inter-vehicle information sharing and collaborative environmental perception. The use of multi-sensor fusion enables collaborative sensing to integrate observations from multiple entities.

Ref. [6] introduces a collaborative driving architecture that incorporates mmWave communication into perception and decision-making processes, thereby enhancing the performance of autonomous vehicle platooning systems. Initial Sensing tasks in cooperative driving can be divided among collaborative vehicles, each of which has a designated sensing range. The leader vehicle then combines the preprocessed sensory data. As a result, multilevel collaborative driving with cooperative sensing is formed, whereby a portion of the group's vehicles share environmental sensing while the group leader makes judgments about the group's driving.

In further studies, methodologies for sensor fusion are often divided into three categories: feature-level, data-level, and decision-level. First, to improve perceptual robustness in mmWave communications, feature-level fusion combines intermediate representations from several sensors using techniques like feature concatenation and element-wise summation. Second, Data-level fusion integrates raw sensor data using probabilistic frameworks including Dempster-Shafer theory, Kalman filtering, and Bayesian inference. Typically, decision-level fusion involves integrating complementary modalities like radar to validate or improve the outputs of one sensor, like optical detections [7].

The collaborative driving scheme outperforms current autonomous driving patterns based on single-vehicle intelligence in terms of efficiency and safety since it is a swarm-intelligence system. Such technologies enable strong target recognition in complex environments, thereby enhancing the safety and real-time responsiveness of autonomous driving systems.

3.3 Mmwave -Enabled Systems and the use of V2X

Building upon cooperative perception, this section ex-

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plores system architectures and decision-making strategies for cooperative autonomous driving control enabled by mmWave communication. V2V and V2I represent the two most fundamental and essential types of communication for enabling cooperative perception and decision-making in V2X systems.

The discussion first centers on V2V communication. MmWave communication offers high-capacity wireless links. From a theoretical standpoint, it supports multi-gigabit data rates, which are essential for autonomous vehicles to handle real-time sensor sharing, vehicle-to-everything (V2X) communication, and cooperative decision-making. A representative use case can be observed on highways, where multiple vehicles can travel in coordinated formations rather than as isolated units. To support such coordination, enhanced beamforming algorithms are employed to reduce processing latency and improve directional accuracy. This approach, referred to as multimodal beamforming, is frequently used to identify pedestrians and objects located between connected vehicles or between a vehicle and a roadside device [8].

V2I communication connects vehicles with networked infrastructure such as traffic signals, RSUs, and edge servers, thereby enhancing vehicle awareness and service capabilities. In addition, these studies considered and analyzed mixed-traffic scenarios involving both autonomous and human-driven vehicles. In Ryuichi Fukatsu's experiment, the goal of the ego vehicle is to pass safely through the intersection. The vehicle attempting to pass through the intersection at the same time is referred to as the target vehicle (Vehicle A). To ensure a safe passage without colliding with Vehicle A, a RSU is deployed at the intersection to enable cooperative perception. Traffic congestion can be reduced when the ego car successfully detects the target vehicle, determines whether an accident is likely to occur, and applies the brakes if it does. [9].

Collectively, these advances contribute to enhanced traffic safety, reduced fuel consumption, improved traffic flow, and increased lane capacity, all of which promote more efficient and sustainable transportation.

4. Challenges associated with application

4.1 Weather Effects on Sensors for Autonomous Vehicles

MmWave communications are highly sensitive to atmospheric and weather-related effects, which pose a significant challenge to ensuring reliable connectivity for autonomous vehicles in real-world environments. Among these effects, precipitation, such as rain, snow and hail, has been identified as a major contributor to signal degradation.

Initially, mmWave signals are attenuated due to absorption by atmospheric oxygen and water vapors.

In conditions of precipitation, the presence of hydrometeors induces absorption and scattering effects on electromagnetic waves, resulting in substantial degradation of mmWave signal strength. The rain attenuation model is commonly expressed as:

$$\alpha_r = aR^b \tag{4}$$

Where αr is the specific attenuation (in dB/km), a and b are coefficients when frequency and temperature are given, and R is the rainfall rate (in mm/h).

$$R = 1.885\times 10^4 \sum_{D_{\min}}^{D_{\max}} N(D)V(D)D^3 \tag{5}$$

In this context, $N(D)$ denotes the raindrop size distribution function, representing the number of raindrops per cubic centimeter with a diameter of D (in mm). V refers to the terminal velocity of a raindrop with diameter D (in m/s).

Because the exact spatial distribution of rainfall is normally unavailable in real time ,rain-induced attenuation in mmWave communications is usually described using its statistical features.

At the same time, the presence of dynamic weather conditions leads to significant variations in image and video intensity, thus compromising their visual quality [10].

For instance, airborne raindrops can introduce characteristic raindrop artifacts on the image surface, leading to reduced image intensity and edge blurring of background objects [11]. Similarly, the presence of heavy snow and hail may enhance the brightness of an image while blurring the edges of objects, making accurate recognition difficult [12]. Therefore, when designing robust mmWave systems for autonomous driving, weather-aware adaptive strategies must be incorporated. This is a key challenge for current research.

4.2 High-Mobility Challenges of mmWave communication

The adoption of mmWave communication in high-mobility vehicular environments has greatly contributed to the advancement of autonomous driving technologies. However, mobility also introduces many challenges to mmWave applications. Owing to the high path loss in mmWave communication, it is necessary to rely on highly directional large-scale antenna arrays for power concentration.

Consequently, maintaining stable links becomes challenging in high-mobility scenarios, as rapid changes in relative position and orientation may break beam alignment.

Moreover, mmWave-based V2X communication must meet stringent requirements for link stability, security, and ultra-low latency, while also addressing inherent challenges like high propagation loss and vulnerability to blockage, all of which are critical to ensure driving safety [13].

4.3 The evolution of autonomous driving systems under the 6G trend

With the emergence of 6G communication concepts, researchers are exploring methods of enhancing mmWave-based V2X networks by integrating ultra-fast, low-latency, and highly reliable connectivity to support massive-scale data exchange in autonomous vehicles environments.

In order to accommodate the growing and evolving requirements of autonomous driving, a significant shift away from traditional communication networks to more versatile and diversified network approaches is needed. The envisioned 6G wireless network seeks to integrate both terrestrial and non-terrestrial elements—including satellite links, UAV-based relays, and high-altitude platforms—to enable ubiquitous and seamless V2X connectivity [14].

5. Conclusion

MmWave communication has become a key supporting technology for autonomous driving, with high directionality and fast data transmission among other advantages. This paper provides a systematic overview of the heretical foundations, system design, channel propagation effects, and practical applications under various external conditions of mmWave communication technology in autonomous driving. The comprehensive analysis shows that mmWave communication is well suited for high-speed and low-latency V2X communication. However, its practical deployment faces several key challenges, including adverse weather and high mobility. This requires advanced weather-aware strategy systems as well as enhanced wireless link adaptation to address these challenges. In addition, the study highlights the 6G and other emerging trends that provide promising directions for improving the robustness and scalability of mmWave in-vehicle systems. The insights presented in this paper are intended to aid the development of self-driving vehicle technology in industry and provide critical support for the reliability of vehicle communications.

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